

Differential die-away analysis system response modeling and detector design

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Abstract

Differential die-away-analysis (DDAA) is a sensitive technique to detect presence of fissile materials such as ^{235}U and ^{239}Pu . DDAA uses a high-energy (14 MeV) pulsed neutron generator to interrogate a shipping container. The signature is a fast neutron signal hundreds of microseconds after the cessation of the neutron pulse. This fast neutron signal has decay time identical to the thermal neutron diffusion decay time of the inspected cargo. The theoretical aspects of a cargo inspection system based on the differential die-away technique are explored. A detailed mathematical model of the system is developed, and experimental results validating this model are presented.

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1. Introduction

There have been many technologies developed to efficiently and comprehensively inspect cargo. Until recently, the primary objectives of cargo inspection technology have been the discovery of contraband such as illicit drugs or large quantities of currency, and conventional threats such as firearms, explosives, and chemical weaponry.

Nuclear material detection differs from conventional elemental analysis. The detectable signatures from fissile material are quite different from the signatures from conventional contraband. SNM (Special Nuclear Materials) or nuclear devices concealed in loaded cargo containers or trucks can in principle be detected by various techniques which provide multiple signatures.

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To be cost effective, the detection of SNM must be accomplished by a multi-tier approach combining several complementary technologies. They include the completely non-invasive/non-interfering and relatively low-cost passive spectroscopic systems that can be massively deployed. They provide the capability to passively detect unshielded or lightly shielded nuclear materials and other radioactive isotopes. However, no passive system can detect nuclear materials that are completely shielded. The presence of shielding may be detected by X-ray based radiography systems that can precede or follow the spectroscopic systems. Together, these two technologies provide a capability to detect unshielded, lightly shielded and heavily shielded nuclear materials, components and weapons that may be illicitly transported in trucks, cargo containers, air cargo containers, or other conveyances. However, the positive confirmation that fissile material is present, or absent, behind the shielding requires the use of active interrogation, where fissions are induced and directly detected.

Differential die-away analysis (DDAA) is an active nuclear inspection technique originally developed to assay

waste containers for the presence of fissile material. The DDAA method was expanded here to the application of SNM detection in transportable cargoes.

When assaying waste containers, the bulk composition is known and of relatively lower density. There is complete access to all parts of the waste container. Fissile material is not deliberately concealed and is likely distributed throughout the container rather than concentrated at the most difficult to detect location. Additionally, run times (or throughput) are less constrained. Finally, waste containers are typically 55 gallon drums, much smaller than a full truck, or even a single pallet.

A cargo inspection system must interrogate large volume containers; it must do so quickly. An inspection system also may not have access to more than one side of a cargo. Active countermeasures may have been taken to make detection more difficult. Because of these differences in application, direct use of unmodified differential die-away would be suboptimal. This paper presents the setup and results from an experimental program to extend the application of DDAA from the realm of waste assay to cargo inspection.

2. SNM detection via DDAA

DDAA is a measurement technique that can be used to non-invasively interrogate a medium for the presence of fissile material. Neutrons in a medium with fissile material have different kinetic properties than neutrons interacting in a medium without the fissile material. This is the signature detected with DDAA.

The differential die-away technique was discovered and patented by J.T. Caldwell, W. Kunz, and J.D. Atencio of the Los Alamos National Laboratory in 1982 [1], and originally used as a way to detect fissile material contamination in waste containers [2]. The technique was first published as a method for transuranic waste assay [3]. Further work was published in the following years with various improvements to the system [4]. Waste assay systems using DDA are still being researched [5].

The differential die-away process works as follows: If a pulse of fast neutrons is generated and directed into a large hydrogenous non-multiplying medium, the population of fast and epithermal neutrons in the medium will peak during the neutron generator pulse and then decay exponentially after the end of the pulse. This decay is due to neutron down-scattering and escape [6]. After a few microseconds, there will be no fast or epithermal neutrons remaining in the medium.

The thermal neutron population inside of the medium will rise quickly, on a sub-microsecond time-scale, due to the thermalization of the fast neutrons. Then as the thermal neutrons are either absorbed or escape, the population will decrease exponentially. The time constant is determined by the physical size and the absorption cross-section of the medium, and is typically a few orders of magnitude slower

than the fast neutrons, with a decay time on the order of hundreds of microseconds.

If the non-multiplying medium has a quantity of fissile material embedded in it, the population of thermal neutrons will still decay in the manner as before. Some of these thermal neutrons will collide with the fissile material, and cause fissions. These fissions then create new fast neutrons.

The number of fast neutrons created by the fission process at any time is directly proportional to the number of thermal neutrons present at that time. The result is that a new source of fast neutrons is created. This source decays exponentially with the time constant of the thermal neutrons.

Fission is the only mechanism that can produce this fast neutron source after the generator pulse. This unique signature is what makes DDAA such an appealing technique to use for the detection of fissile material.

An additional signal of delayed neutrons is produced. These neutrons are not time-correlated (when compared to the time-scale of a single pulse). This signal competes with the natural background. Additional detections above background after the pulse and DDAA signal have died away are also an affirmative indication of the presence of SNM.

Time-dependent, asymptotic, one-group diffusion theory sufficiently describes the physics of these systems. A thorough mathematical treatment of the kinetics may be found in Ref. [7] or [8]. In most measurements, the higher diffusion modes will have died-away long before the time when the differential die-away signal becomes significant.

In the asymptotic case for a homogeneous medium, the number of thermal neutrons in a non-multiplying medium produced from a short neutron pulse impinging upon the medium is predicted from one-group neutron diffusion theory to decay in time with a single exponential and a decay time α (a more convenient unit than its reciprocal, the decay constant τ). The number of neutrons in the medium at time t after the end of a pulse is given by

$$N(t) = e^{-t/\alpha}. \quad (1)$$

The asymptotic time constant of this decay is dictated both by the absorption in the medium and by the leakage out of the medium and is given by

$$1/\alpha = \Sigma_a v (1 + L^2 B^2) \quad (2)$$

where, Σ_a , the macroscopic absorption cross-section, $v = 0.22 \text{ cm}/\mu\text{s}$, the velocity of a thermal neutron, L^2 , the thermal diffusion length, and B^2 , the buckling of a parallelepiped, have their normal nuclear engineering meanings. These equations describe asymptotic decay behavior and are only dependent on the fundamental mode of the diffusion equations.

For a wide pulse, while the neutron generator is on, the thermal neutron flux can be described by

$$N(t) = I_0 (1 - e^{-t/\alpha}) \quad \text{for } [0 \leq t \leq T_p] \quad (3)$$

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